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APPLICATIONS OF "PV OPTICS" FOR SOLAR CELL AND MODULE DESIGN

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ABSTRACT: This paper describes some applications of a new optics software package, *PV Optics*, developed for the optical design of solar cells and modules. *PV Optics* is suitable for the analysis and design of both thick and thin solar cells. It also includes a feature for calculation of metallic losses related to contacts and back reflectors.
Keywords: Solar Cell Design – 1: Optical Properties – 2

1. INTRODUCTION

High-efficiency solar cells involve a number of features that are difficult to handle by simple optics. An optical design and analysis software package for solar cells and modules must include capabilities to handle: (i) nonplanar interfaces such as those required for optimizing light-trapping; (ii) thick devices such as crystalline silicon solar cells as well as thin cells based on a-Si, CdTe, and CIS; (iii) antireflection and dielectric coatings, (iv) metallic absorption arising from contacts and back reflectors; and (v) thicker materials such as glass and encapsulants used in modules.

We have developed a new, commercial, computer software package, *PV Optics*, for the optical design and analysis of solar cells and modules. This paper describes some applications of this software package.

2. FEATURES OF *PV OPTICS*

PV Optics is an easy-to-use software that accurately models the optics of any solar cell or module, and provides information needed to design a device with maximum-effective light-trapping and optimum photocurrent. *PV Optics*' sophisticated model uses the coherence length of light as a criterion to categorize various regions of a cell as "thin" or "thick" – the former have thicknesses less than the coherence length of light and include interference and polarization effects; the latter are much thicker than the coherence length and are treated on the basis of ray optics. The model separates a multilayer structure into several composite layers each as a "thin" or "thick" group. Each group of layers is analyzed and the entire structure is reassembled. Regions such as glass superstrates or encapsulation layers having thicknesses greater than a few microns, and textured structures, are treated in a noncoherent regime. Thin and specula layers such as those used for antireflection (AR) coatings in a-Si devices are treated as coherent regions.

PV Optics:

- Accommodates device design for single and multijunction cells, with as many as three active semiconductor layers plus cover glass, encapsulation, AR coating, buffer, and metal backing.
- Calculates the light-trapping impact of nonplanar (textured or intentionally rough) interfaces of any of the device layers.
- Accurately calculates interference effects (caused by coherence of light) of very thin layers such as AR coatings or thin-film semiconductor materials.
- Includes default refractive index and extinction coefficient values for crystalline silicon, amorphous silicon, glass used for encapsulation, encapsulation materials such as EVA, and buffer layer.
- Calculates maximum achievable current density (MACD in mA/cm^2) for each semiconductor layer, providing a benchmark for cell performance.
- For each device, automatically and clearly plots:
  – Reflection, transmission, semiconductor absorbance, and metal absorbance, each as a function of wavelength
  – (For multijunction devices) absorbance for each separate layer plus total absorption
  – Absorbance by wavelength for typical sunlight (AM1.5), predicting actual cell performance
- Photon absorbance as a function of depth within each semiconductor layer—facilitating selection of optimum thickness(es) (this data can be used in an electronic model like AMPS or PC1D for complete cell performance prediction).

PV Optics can be used for optimizing a variety of cell parameters, such as cell absorber thicknesses, the structure of the texture, AR coating parameters, and the back-reflector design. Here, we will demonstrate the capabilities of the package by specific examples. The model is a user-friendly tool using a "Windows" environment. It requires as input the optical constants of each layer as a function of wavelength and the layer thicknesses. Texture is simulated by allowing the user to select appropriate geometric features in addition to co-planar layers. Computing times depend significantly on the conditions chosen and can vary from minutes to hours. The examples we present are intentionally kept simple to demonstrate the capabilities of the package, and show that results are often obtained that would not have been expected intuitively.

3. OPERATING *PV OPTICS*

PV Optics (Version 1) for the PC comes on a single 3.5" floppy disk. The software requires an IBM compatible PC/60 MHz (or a higher speed), a minimum of 8 MB RAM, windows, a VGA monitor, and a color printer (can also operate with a black & white printer).

3.1 Selection of the Device Configuration

PV Optics Version 1, starts with a generalized device configuration as illustrated in Fig. 1. From this, one can select a desired device configuration. The device may include glass, encapsulation, AR coating, three semiconductors, a buffer, and metal. The device-configuration choice is made by simply deleting portions of the device configuration that does not correspond to the desired device, with a click of a mouse.

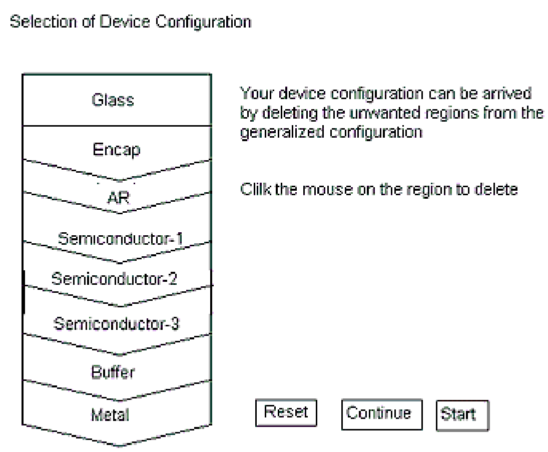


Figure 1: Illustration showing how the device configuration can be selected from the total module configuration.

Once the device configuration is arrived at, the program expects data pertaining to each layer and its interfaces. There is a “page” of each layer. The software provides default values for the interface type, thickness in microns, and n and k of each region. The default values correspond to standard materials used in PV manufacture. One can use the default values or change them simply by a click. The antireflection page provides the default values for the interface type, n1, k1, thickness1, n2, k2, and thickness2 for a two-layer AR Coating (n1, n2 are the refractive indexes and k1, k2 are the extinction coefficient). The selection of semiconductor page provides choices of up to three junction cells, and options to select the material "Silicon" or "Amorphous-Silicon," "Amorphous-Silicon Top," "Amorphous-Silicon Middle," or "Amorphous-Silicon Bottom." Additional semiconductor data can be incorporated at request.

3.2 Results are Displayed as Graphs

There are seven types of graphs: (1) Reflectance / Transmittance, (2) Absorbance, (3) Weighted Absorbance, (4) Photon Flux, (5) Reflectance / Transmittance (Non-Coherent), (6) Reflectance / Transmittance (Coherent), and (7) Weighted Absorbance.

The graphs may be saved as a bit-map (.bmp) file by selecting "Export" from the file menu. This will bring up the files window where you will be able to select drives, directories, and filenames. The files window will also insure that you give the graph a designated extension of ".bmp." Once you have selected or entered the filename that you wish to use, click on the "OK" button. Make sure that you are in the directory that you wish to save the file in. If you click on the "OK" button while the filename still shows "*.bmp," then the window will show you a list of only those files that have been saved as bit-maps.

4. RESULTS

In this section, we present results of calculations, for a number of cell and module structures, as examples of the capabilities of *PV Optics*.

Example 1 is a comparison of the optical characteristics of a silicon solar cell before and after encapsulation. Fig. 2 shows the reflection and absorption of a Si solar cell with the following features: textured front with a two-layer AR coating consisting of 710 Å of Si_3N_4 (refractive index =1.95) on 100 Å of SiO_2 (refractive index=1,45); the texture height is 3 µm, thickness of Si cell is 250 µm, the backside of the cell is also textured with Al metallization. The calculated MACD = 41.02 mA/cm^2. Fig. 3 shows similar plots after the cell is encapsulated. The structures of the cell and the module are illustrated in each figure. The MACD value after the encapsulation is 38.75 mA/cm^2. Thus there is a loss of approximately 2.3 mA/cm^2 associated with encapsulation. From Fig. 3, it can be seen that after encapsulation there is a significant increase in the reflection

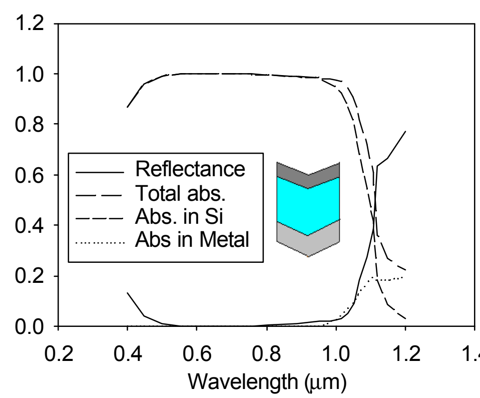


Figure 2: Calculated characteristics of a silicon solar cell (see text for the cell structure).

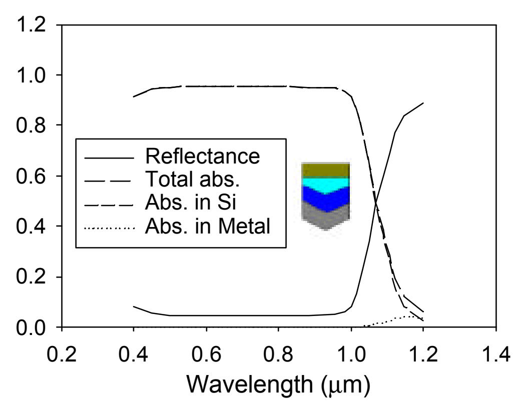


Figure 3: Calculated characteristics of the cell shown in Fig. 2, after encapsulation (see text for the cell structure).

(in the wavelength range of 0.5µm – 1µm). The loss caused by this increase in reflection is offset by a decrease in the reflectance in the wavelength range of 0.4µm – 0.5µm.

From Figs. 2 and 3 we see an expected behavior of the reflectance – the cell reflection has a broad null in the wavelength range of 0.5 µm and 0.9 µm, while the module reflectance is dominated by the glass reflection. These figures also show absorption in the back metal is slightly less in the encapsulated case.

We can now compare the optical characteristics of a frontside textured cell with the double-sided textured cell of Fig. 2. To do this, we consider the cell of Fig. 2 and change the backside of the cell to a planar interface. The calculated results are shown in Fig. 4. Notice that the loss in the metal is lower, yet the MACD decreases to 40.66 mA/cm^2. The lower loss in the back planar surface, compared to the back textured surface can be explained in a rather oversimplified manner as follows. The light that reaches the backside undergoes one reflection at this planar surface, while a textured interface leads to more than one reflection. Because each reflection from the Si-Al interface is accompanied by metallic absorption, the textured interfaces lead to higher metal absorption. Clearly, the metallic loss depends on a number of parameters that include angle of incidence at the Si-Al interface and the intensity of light incident at the interface. Interposing a buffer layer of low refractive index between the semiconductor and the metal can mitigate this loss. This feature is illustrated in Example 3.

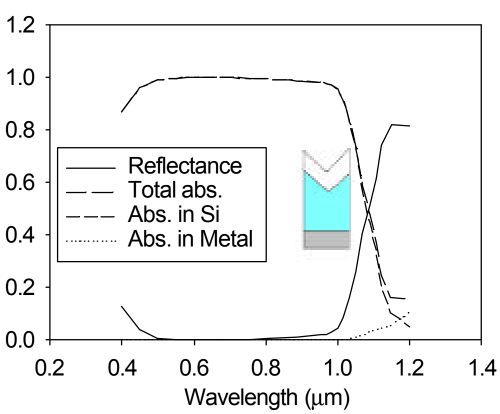


Figure 4: Calculated characteristics of a Si solar cell with frontside textured (see text for cell structure).

The second example demonstrates the ability of *PV Optics* to automatically recognize and deal with structures that are thinner than the coherence length of the incident light. Fig. 5a shows the results of *PV optics* for a structure consisting of a 0.5-µm-thick layer of a-Si on an Al substrate. In this "coherent" mode, the output shows interference fringes. Under this situation, *PV Optics* also performs calculations based on "incoherent" conditions. This result is shown in Fig. 5b.

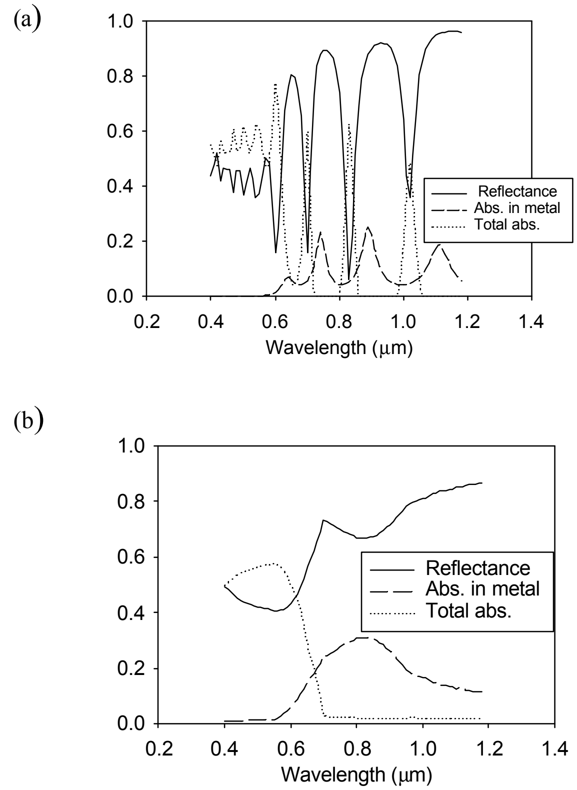
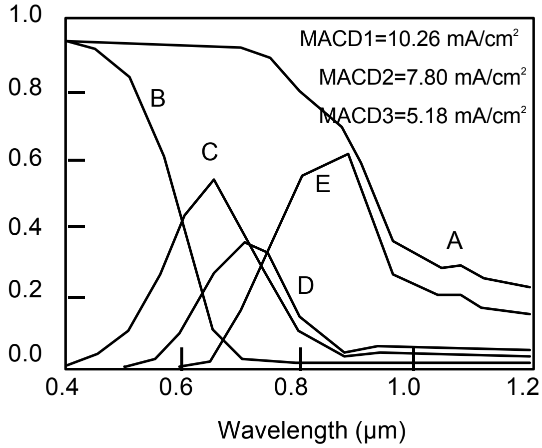
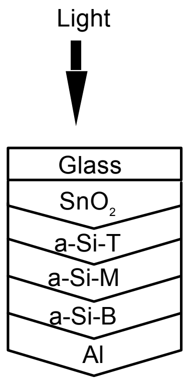


Figure 5: Calculated characteristics of a a-Si solar cell (see text for the cell structure) using *PV Optics* in (a) coherent mode and (b) noncoherent mode.

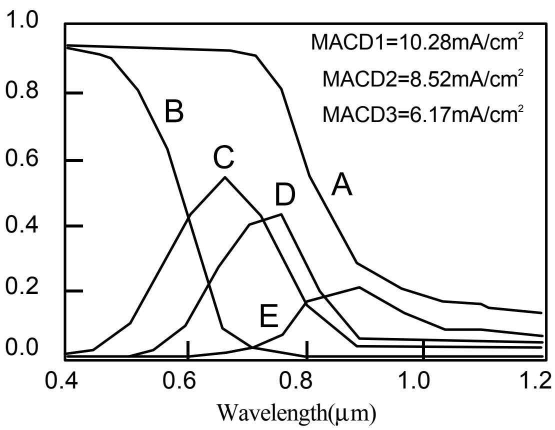
Example 3 pertains to an assessment of metallic losses in textured a-Si solar cells. Often the losses associated with back reflectors are assumed to be small. This assumption is generally made because reflection coefficients of many metallic reflectors reach close to 0.97 in air. However, this situation is quite different in a solar cell. The reflection at a high-refractive-index semiconductor and a metal can be greatly reduced. The light transmitted into metal is readily absorbed, leading to a significant loss of the optical energy. *PV Optics* can be very effectively used to calculate and gain an understanding of such losses. In particular, it is of interest to determine the effect of a buffer on the back reflection and metallic losses. Figs. 6a and 6b show the results of *PV optics* calculating the absorbance as a function of wavelength in two three-junction cell structures – one without buffer and the other with buffer. The cell structures are illustrated in each figure. The light enters the cell through a nonabsorbing SnO_2. The symbols T, M, B refer to top, middle, and bottom junction layers. The band gaps, Eg_i (i = T, M, B), have values such that $Eg_T > Eg_M > Eg_B$. The thicknesses of the top, middle, and the bottom layers, used in these calculations are assumed to be 0.3, 0.2, and 0.1 µm, respectively. The buffer layer consists of 0.25-µm-thick MgF_2. These modeling cases are simplified optical representations of a-Si "superstrate" cell. Figs. 6a and 6b show absorbance in each semiconductor layer as well as the total absorbance. We see that, for the structure of Fig. 6a without buffer, the MACD values corresponding to each layer are: 10.3, 7.8, and 5.1 mA/cm^2 in the three a-Si layers and a metal loss of 9.5 mA/cm^2 for the structure without MgF_2. By introducing the buffer layer, the MACD values are 10.3, 8.2, and 6.2 mA/cm^2, with a metal loss of 3 mA/cm^2. It is of interest to note that the MgF_2 "backreflector" affects the current density not only in the semiconductor layer adjacent to it, but also in the a-Si layers further away.

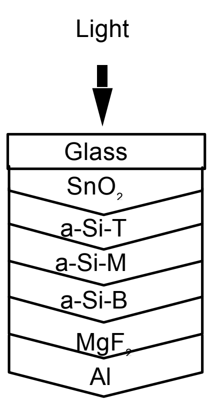




A– Total absorbance
B–Absorbance in semiconductor 1
C–Absorbance in semiconductor 2
D–Absorbance in semiconductor 3
E–Absorbance in metal

Figure 6a. Absorbance in simulated 3-layer a-Si superstrate cell with Al back reflector but no buffer.





A– Total absorbance
B–Absorbance in semiconductor 1
C–Absorbance in semiconductor 2
D–Absorbance in semiconductor 3
E–Absorbance in metal

Figure 6b. Absorbance in simulated 3-layer a-Si superstrate cell with MgF_2/Al back reflector.

6. CONCLUSIONS

We have presented a brief description of *PV Optics* and discussed its results for a number of solar cells. The cell structures are used only as examples to demonstrate capabilities of this software. This software can be used for analysis of thick as well as thin cells. We have identified why in many instances the current densities observed in actual devices are less than those predicted from simpler analytical considerations. These discrepancies are not due to inadequate texturization or randomization of light, but rather to increased absorption losses in the rear-contact metallization as the light hits the metal from a layer with a refractive index n>1 and at oblique angles.

The present version of *PV Optics* (Version 1) is a two-dimensional model, and the light can be made incident only from the topside. The newer versions will include a number of modifications requested by PV community. *PV Optics* has other applications in modeling and design of display devices.

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